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Polymer-modified pervious concrete for durable and sustainable transportation infrastructures

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HIGHLIGHTS

- Polymers affected both mechanical and volumetric performance of pervious concrete.
- Polymers delayed hydration reactions of cement particles.
- Compaction ability and mechanical performance were improved by some of the polymers.
- Porosity and drainability were not substantially modified by the use of polymers.
- Polymer form (latex or powder) showed to provide different effects on performance.

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ABSTRACT

Pervious concrete is widely considered as an optimal material to manage storm waters in built environments as well as to provide several other environmental benefits. Despite the broad capabilities pervious concrete pavements have exhibited a high failure rate so far. Causes are mainly related to poor design, inadequate construction techniques including compaction, and heavy vehicular traffic. Performance of pervious concrete can be furthermore improved by modifying the cement matrix through polymer modifications, for instance. Polymers could indeed have the capability of improving mechanical performance, particularly flexural strength, without reducing drainability and void content.

Four polymers have been tested in the present research and preliminary analyses on polymer-modified cement grouts and mortars were conducted during the first phase of the study; polymer-modified pervious concrete mixes were then prepared and further tested to evaluate the inclusion of polymers depending on the type and content.

Results showed a delayed curing of polymer-modified mixes as well as an increased mechanical resistance and durability to raveling and freeze-thaw cycles; polyvinyl acetate polymer demonstrated to be a very good option.

1. Introduction

The U.S. Environmental Protection Agency published a Porous Pavement fact sheet [35] listing the advantages of pervious pavements. The main advantages are: water treatment by pollutant removal due to natural filtration effect, less need for curbing and road-side storm sewers, improved safety because of increased skid resistance, and recharge to local aquifers whenever a granular unbound foundation is designed below the porous surface layer. Although asphalt porous pavements are well-known and adopted as friction course in several road projects worldwide, especially in Europe, permeable concrete pavements still face several difficulties to be fully implemented, particularly on mid-to-high traffic roads.

The main issues are related to raveling, freeze-thaw resistance, durability in general, and construction abilities by contractors, principally. Depending on compaction energy [11,12] during construction operations, the same mix-design can indeed provide variable performance, very low mechanical resistance but great permeability when poorly compacted (i.e.; hand-rolling) up to evidently good structural behavior with low permeability when over compacted (i.e.; steel drum rolling with multiple passes). The need for a perfect balance between resistance and permeability, hard to achieve, usually leads to tenuous results. According to the EPA [35], approximately 75 percent of pervious concrete pavements have failed so far. This has been attributed to poor design, inadequate

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construction techniques, low permeability soil, heavy vehicular traffic, poor maintenance and consequent clogging.

For a specific hydraulic potential, surely the main feature of pervious concrete to be preserved, the mechanical behavior has been improved by many research studies varying the gradation curve [33,3], the amount of water and cement, admixtures content, including several type of fibers [13,14,2], adding small amounts of fine sand [25,13,14] into the mix, etc.

To date, polymer modifications of pervious concrete material interested very few studies [27,34,25,31,9] although the science of altering the mechanical behavior of concrete materials through polymers gained consensus in civil engineering (mainly structures) since decades [24]. Polymers indeed cover a wide variety of applications due to their multiple peculiarities and have the potential to provide for resistance and durability without neglecting the ability to permeate.

The present paper aimed at investigating the potential benefits provided by several polymer additions into pervious concrete mix; the research study was conducted on a step-by-step basis evaluating the effects of several types of polymer and contents on 1) the cement grout (water, cement, and admixtures), 2) the cement mortar (grout plus sand), and 3) the pervious concrete mix (cement mortar and aggregates).

2. Background

Polymers have been included into cement mixes since long time to modify the concrete behavior during fresh and hardened state. They are also commonly adopted for concrete maintenance as a fast and cost-effective repair intervention in structures and rigid pavements. Results can vary upon the type of polymer, water/cement ratio, polymer/cement ratio, type of the aggregate and curing conditions, just to cite few.

Generally, polymers are large molecules made up of many individual monomers connecting each other end to end; they can be made up of one single type of monomer (homopolymer; i.e. polystyrene) or more than one type (copolymer; i.e. Ethylene-vinyl acetate) resulting in a broad range of properties. Common classification of polymers includes thermoplastics and thermosets, and elastomers or rubbers. Thermoplastics (polystyrene and polyolefin, for instance) have the ability to soften when exposed to heat and recover when cooled down; they can be repeatedly softened and solidified depending on heat because of their relatively weak intermolecular forces (long and linear chains). Thermosets, instead, solidifies or "sets" irreversibly when heated (epoxy resin, for instance); once formed, the crosslinking of polymer chains (stronger three-dimensional networks of covalent bonds) resists to heat softening and mechanical deformation. Elastomers (natural rubber, for instance) exhibit "occasional" crosslinking – low cross-link density – able to provide a sort of memory to the material at operating temperatures so that it recovers strain after unloading; some elastomeric polymers are thermoplastics (i.e.; styrenic block copolymers) while others are thermosets (i.e.; polyurethane). The physical characteristics of the polymers affect the properties of the fresh and hardened cement mortar and therefore the performance of final concrete. Polymers can also be distinguished in ionic or nonionic, depending on the atomic charge of the side chains. Ionic polymers tend to locate around the particles (cement grains, for instance) and behave as a surfactant dispersing the clinker grains, reducing water demand and easing hydration.

Polymers are also available in several forms; generally, they can be distinguished in latex (suspension of the polymer in water), powder, or resin (liquid form). The latex-modification is the most common form of polymer addition due to its relatively simple incorporation into the mortar or concrete; it is added during the mixing phase and the latex-relative water content should be considered as participating into the overall water content of the mixture.

Several additions have been tried as to increase pervious concrete performance with the majority of them coming from the standard concrete practice. Silica fume, commonly added as a fine powder, is one of the easiest ways to enhance concrete mechanical and functional performance; the pozzolanic reactions between the silica fume and free calcium hydroxide in the paste allow for increased compressive strength and abrasion resistance as well as reduced permeability of concrete to chloride ions [29]. Yang and Jiang [36] showed that the combination of silica fume and plasticizer can significantly enhance pervious concrete compressive (up to 50 MPa) and flexural strength (up to 6 MPa) without undermining permeability and abrasion resistance. However, other studies highlighted that silica fume greatly increased the water demand of the mix and other chemical admixtures (i.e. plasticizers) were therefore needed [28]. High-range water-reducer admixtures are generally applied to concrete mixes to affect the set time of concrete. However, Amde and Rogge [2] found that high-range water reducers must be used with caution into pervious concrete mix since a large dosage can cause segregation of cement from the aggregate and a consequent settle at the bottom, forming therefore an impermeable layer.

Kevern et al. [25] added SBR polymer (Styrene-Butadiene-Rubber) in latex form as a way to improve pervious concrete characteristics. SBR has been also approved by the Federal Highway Administration for latex-modified concrete used in bridge deck overlays, for instance. In particular, it was found that SBR improved strength (particularly the split tensile strength because the latex network is relatively strong in tension) and freeze-thaw resistance at low cement contents. Wang et al. [37] replaced approximately 10% of Portland cement with SBR latex and found that the specimens increased the tensile strength resistance, indicating an improved resistance to cracking.

The interaction between the polymer particles and cement hydrates greatly affect the film formation, the micro-structure of the polymer-modified concrete material, and therefore the final performance and durability. Beeldens et al. [10] studied the film forming capacity of the polymer dispersion under different curing conditions (98%, 86%, and 60% of relative humidity); the cement hydration was retarded by the polymer whenever a humid curing was adopted and testing after 28 days resulted in lower performance of unmodified reference concrete. However, flexural strength was increased by 25% after 7 days if a dry curing (at 60% relative humidity) period was adopted. This typical behavior [30] is due to water retention of the polymer dispersion and to the encapsulation of cement particles by the polymer dispersion; the hydration of the cement is furthermore retarded when the polymer/cement ratio is increased. If a dry curing period is introduced, then the polymer film starts to form and an increase in flexural strength was measured with increasing polymer/cement ratio [10].

The relative humidity during curing proved to have strong influence on film formation and on the drying rate. Higher relative humidity generally leads towards lower drying rate and thus the film forming temperature of the dispersion is affected. Low drying rates entail smaller amount of energy for the polymer particles to combine into a continuous film. Therefore, the film formation temperature is reduced.

3. Experimental plan and methodology

The objective of the experimentations was to evaluate the improvements on pervious concrete material due to polymer modifications; in particular, the effectiveness of polymers on stiffness, mechanical performance, and long-term durability were analyzed.